The Implicit Cost of Carbon Abatement During the COVID-19 Pandemic

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Motivation

Forbes

Apr 22, 2020, 01:00pm EDT

Silver Lining Of Pandemic Shows It's Possible To Solve Climate Change

SAP BRANDVOICE | Paid Program

Innovation

By Victoria Rochard, Thought Leadership, SAP

Scrolling through Facebook recently, there was one

Motivation

Impact of the pandemic on carbon emissions:

- Is there a silver lining? If so, how thick is it?

EU Green Deal:

- By 2050, reach net zero CO2 emissions by 2050
- By 2030, reduce emissions by at least 55% vs 1990 levels

Debate on how to achieve those goals:

- Is it possible without sacrificing **economic growth**?
- Or can we decouple growth from emissions?
- What are the implicit costs of different strategies?

We focus on the case of Spain and its power sector.

Research Question

What are the implicit costs of carbon abatement according to alternative strategies?

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1. **Slowing down economic activity**:
   - Pandemic as a natural experiment
   - Caveat: Pandemic was a shock, not planned "degrowth"
   - Pandemic is proxy of slow down, holding economic structure fixed

Research Question

What are the implicit costs of carbon abatement according to alternative strategies?

1. **Slowing down economic activity**:
   - Pandemic as a natural experiment
   - Caveat: Pandemic was a shock, not planned "degrowth"
   - Pandemic is proxy of slow down, holding economic structure fixed
2. **Investing in renewables**:
   - How much investment in renewables would we need to achieve the same carbon abatement as that observed during the pandemic?
   - Can be considered as part of a decoupling strategy

Steps of the analysis

1. We measure the effects of the pandemic on **emissions reductions**.
   - Counterfactual predictions in the power sector.
   - Emissions from other sectors (from external references).
2. We measure the pandemic effects on the Spanish economy.
   - Counterfactual forecasts of **GDP**.

$\longrightarrow$ After steps 1 and 2, calculate **implicit cost of carbon** from slowing down economic activity

3. Simulate **investments** in renewables necessary to achieve CO2 reductions similar to those observed in the power sector during the pandemic.
4. Compare the implicit cost of carbon abatement from the pandemic versus from investing in renewables.

Predicting Counterfactual Electricity Consumption

- **Objective:**
  - Predict counterfactual electricity consumption in absence of the pandemic
    - Obtain precise hourly predictions, which will be used later in electricity market simulations
    - Use only covariates that are not affected by the pandemic
- **Data:**
  - Hourly consumption in Spain from 2015-2020
  - Weather variables: temperature, precipitation, wind speed, and wind direction
  - Holidays
  - Date/time fixed effects (seasonality)
  - Time trends

Predicting Counterfactual Electricity Consumption

- **Predictive machine learning model of consumption:**

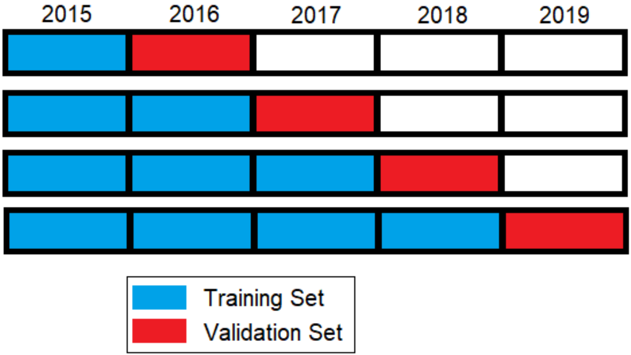
$$Y_t(0) = g(\mathbf{X}_t) + \varepsilon_t$$

- Covariates $\mathbf{X}_t$: weather and date/time fixed effects
- Model trained and cross-validated with past data (2015-2019)
  - Model selected based on **out-of-sample** performance
  - Using forward chaining cross-validation (Hyndman and Athanasopoulos, 2018):
- $g()$: Gradient Boosted Trees (GBT; Chen and Guestrin, 2016)
- Impact of the pandemic on electricity demand:

$$\hat{b}_t = Y_t(1) - \hat{Y}_t(0) = Y_t(1) - \hat{g}(\mathbf{X}_t)$$

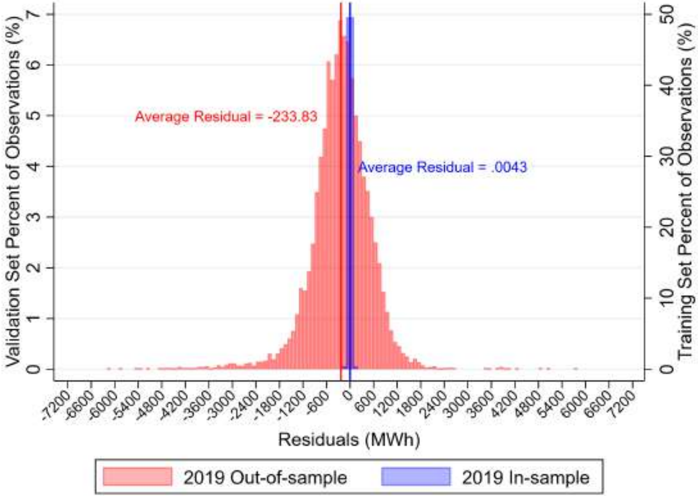
Main assumption: relationship $g()$ between energy consumption and covariates would not have changed from 2019-2020.

Forward Chaining Cross-Validation



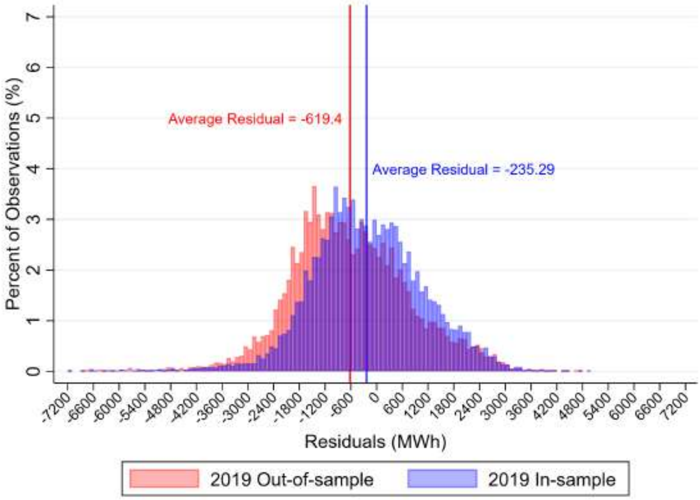
- Choose model based on prediction errors (RMSE) in 2019
- GBT results in RMSE of 809 MWh; compared to avg. hourly consumption in 2019 = 28,528 MWh; or std. dev. = 4,525.

Cross-Validation Results – ML



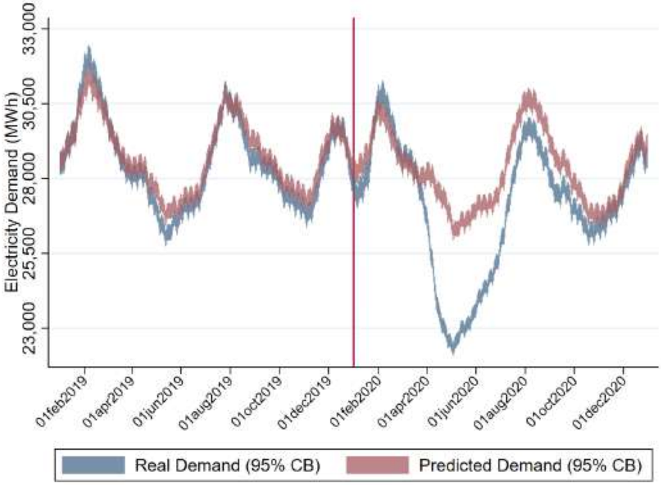
Average out-of-sample residual is less than 1% of average hourly consumption

Cross-Validation Results – fixed effects model



Day of year FE; hour of day interacted with weather; lagged (up to 3) weather

Counterfactual Consumption in the Power Sector



Notes: Based on 30-day moving averages.

Counterfactual Emissions in the Power Sector

- Use the hourly consumption estimates to **simulate the hourly electricity market outcomes** with and w/o the pandemic
- Simulations based on De Frutos and Fabra (2012)
- Identify which plants would have been dispatched $\longrightarrow$ obtain carbon intensity of the market

Counterfactual Emissions in the Power Sector

- Use the hourly consumption estimates to **simulate the hourly electricity market outcomes** with and w/o the pandemic
- Simulations based on De Frutos and Fabra (2012)
- Identify which plants would have been dispatched $\longrightarrow$ obtain carbon intensity of the market
- We take all else as given:
  - Hourly availability of renewables
  - Monthly hydro availability
  - Existing capacity of gas/coal/nuclear plants
  - Daily prices of gas/coal/CO2
  - Caveats: nuclear availability and gas/coal/CO2 prices may have changed

Simulated Change in Emissions from Power Sector

Spanish power sector carbon emissions, measured in MtCO2

	Simulations With Counterfactual Demand	Simulations With Realized Demand	Difference
Coal	3.23	3.08	0.15
Gas	21.69	18.00	3.69
Cogen + Others	11.16	10.87	0.29
Total	36.07	31.94	4.13

Notes: Assuming competitive market structure. Results from strategic equilibrium presented in the paper.

Almost 90% of abatement due to reduced gas usage.

Emissions from Other Sectors

CO2 Emissions for Other Sectorsin Spain

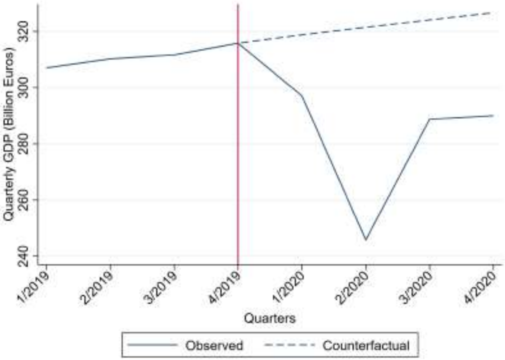
	MtCO2 Emissions			
	2019	2020	Diff.	Pct. Diff.
Domestic Aviation	5.64	3.00	2.63	46.68
Ground Transport	84.83	75.40	9.43	11.12
Industry	62.25	55.63	6.62	10.64
Residential	36.70	36.14	0.56	1.53

Source: (Carbon Monitor; Liu et al., 2020)

Total abatement in Spain during 2020 = 23.14 MtCO2

Counterfactual Economic Activity

- Counterfactual GDP based on forecasts from Bank of Spain
- Forecasts made at the end of 2019 (no info. about pandemic)



- Total GDP loss in 2020: 169.37 Billion Euros
- Implicit cost of carbon = 7,319 €/Ton CO_2

Investing in Renewables

- Power market simulations (De Frutos and Fabra, 2012)
- Vary types of investments: increase solar or wind capacity
- Keep simulations that yield the same emissions reductions in the power sector as the pandemic

		Investment Costs (M EUR)		
	Emission Reductions (M Tons)	Total	Annualized Investment+O&M	Implicit Cost of Carbon (EUR/Ton)
Pandemic	4.13	-	-	-
Solar Investments	4.53	6,890.11	275.60	60.80
Wind Investments	4.06	6,122.97	244.92	60.34

Notes: Assuming competitive market structure. Results from strategic equilibrium presented in the paper. Costs from IRENA (2020).

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The implicit cost of carbon under each strategy is:

1. Slowing down economic activity: 7,319 €/Ton CO2
2. Renewables: 60 €/Ton CO2

Conclusions

Carbon abatement may be obtained by slowing down economic activity and/or investing in renewables

1. Results suggest that simply halting growth is too costly
   - The magnitude of the losses versus the relatively small abatement make that clear
   - Carbon abatement was short-lived, while economic losses are expected to be long-lasting
2. Investments in renewables can achieve abatement at much lower cost
   - Renewables could even provide more benefits in terms of economic stimulus
3. Of course, these strategies should be complemented with:
   - Improving energy efficiency, revolutionizing transport and mobility, etc.

Thank You!

Comments? Feedback? Questions?

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Appendix: Why Machine Learning?

- ML flexibly accounts for nonlienarities and high-order interactions
- Agnostic about which variables are most important
- Agnostic about functional forms
- Best **out-of-sample** performance
  - Will compare to fixed effects models

Appendix: Cross-Validation Results

Using RMSE as accuracy metric. Values are in MWh.

Panel A: Validation Year RMSE				
Model ID	2016	2017	2018	2019
ML 1	1155.88	934.42	856.18	809.13
ML 2	1160.67	984.78	871.45	815.45
ML 3	1517.53	1219.22	1165.42	1063.05
ML 4	1532.10	1266.84	1152.23	1083.03
FE 1	1786.17	1837.05	1878.91	1998.73
FE 2	1856.67	1836.63	1890.78	2019.15
FE 3	2931.66	1814.91	1899.57	2009.61
FE 4	1936.32	1227.76	1361.87	1550.50

Compared to avg. hourly consumption in 2019 = 28,528 MWh; or std. dev. = 4,525.

Appendix: Details on Specifications

Using RMSE as accuracy metric. Values are in MWh.

Panel B: Details on Model Specifications				
Model ID	ML Hyperparameters			
	ntrees	max_depth	shrinkage	minobspernode
ML 1	2000	10	0.05	20
ML 2	2000	30	0.05	20
ML 3	2000	10	0.5	20
ML 4	2000	30	0.5	20
Model ID	Fixed Effects Included			
FE 1	Month of year			
FE 2	Week of year			
FE 3	Day of year			
FE 4	Day of year; hour of day interacted with weather			

Appendix: Inference With Machine Learning

Let b_t be the effect of the pandemic.
$Y_t(1)$ is realized demand, and $Y_t(0)$ is counterfactual demand

$$\hat{b}_t = Y_t(1) - \hat{Y}_t(0)$$
$$\hat{b}_t = Y_t(0) + b_t - \hat{Y}_t(0)$$
$$\longrightarrow b_t = \hat{b}_t + \hat{Y}_t(0) - Y_t(0)$$
$$\longrightarrow b_t = \hat{b}_t - \hat{r}_t$$

Where $\hat{r}_t$ are residuals from the prediction of $Y_t(0)$

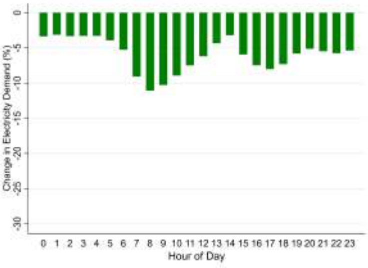
Then we also have (assuming $\hat{b}_t$ and $\hat{r}_t$ independent):

$$Var(b_t) = Var(\hat{b}_t) + Var(\hat{r}_t)$$

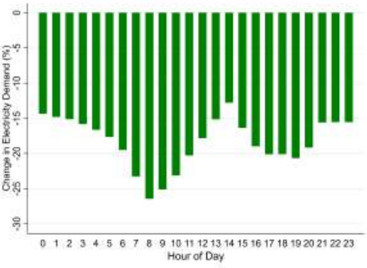
Note that $\hat{r}_t$ cannot be observed, so we proxy it with the variance of the (out-of-sample) residuals from 2019

Effect of the Pandemic on Electricity Consumption

Reduced electricity consumption by hour of the day



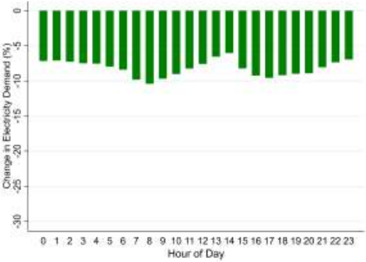
1st Partial Lockdown
(March 11 - March 28)



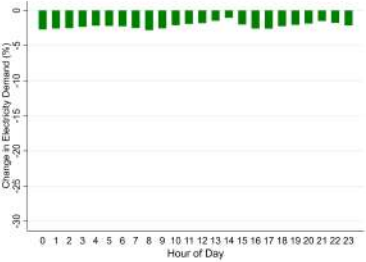
Full Lockdown
(March 29 - April 10)

Effect of the Pandemic on Electricity Consumption

Reduced electricity consumption by hour of the day

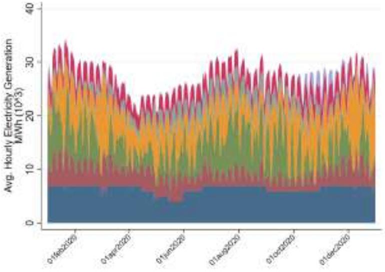


Partial Lockdowns
(April 11 - August 14)

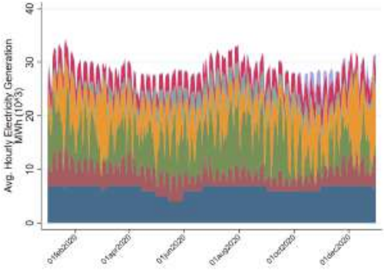


Rest of Year
(August 15 - December 31)

Generation Mix in the Power Sector



(a) Realized consumption



(b) Counterfactual consumption

Notes: Using data up to September 2020. Assuming competitive market structure. Results from strategic equilibrium presented in the paper.

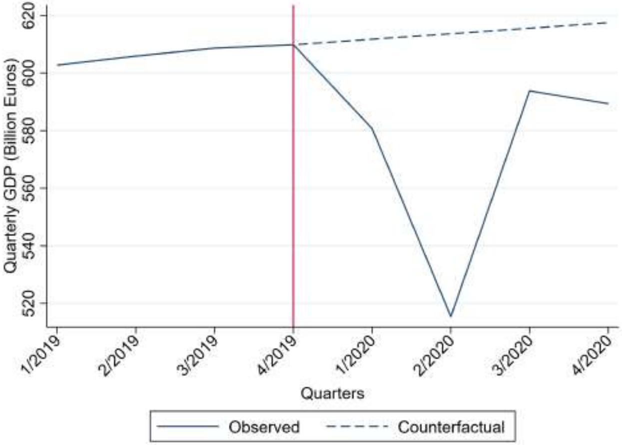
External Validity: France – Emissions

Sector	MtCO2 Emissions			
	2019	2020	Diff.	Pct. Diff.
Domestic Aviation	2.33	1.29	1.04	44.53
Ground Transport	116.62	104.80	11.82	10.14
Industry	61.67	54.47	7.20	11.67
Residential	79.87	75.75	4.12	5.16
	Counterfactual	Realized	Diff.	Pct. Diff.
Power (lower bound)	22.68	21.79	0.90	3.95
Power (upper bound)	171.28	164.50	6.77	3.95
Total (lower bound)	283.17	258.10	25.07	8.85
Total (upper bound)	431.77	400.81	30.96	7.17

Lower bound assumes carbon intensity of 49 gCO2/kWh (avg. of sector)

Upper bound assumes carbon intensity of 370 gCO2/kWh (CCGTs)

External Validity: France – GDP



Short-term GDP loss = 179.11 Billion Euros

Implicit cost of carbon = 5,785 Euro/Ton for France.

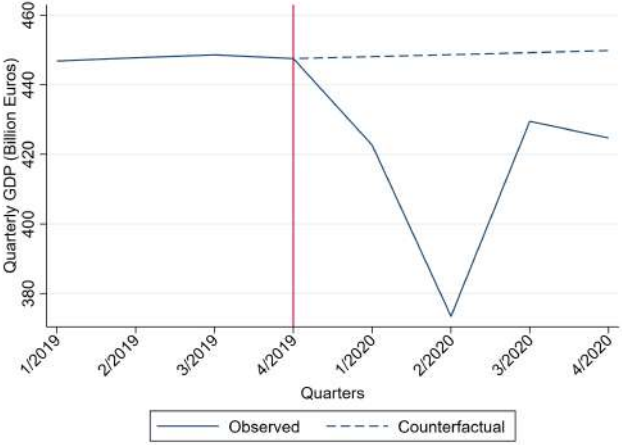
External Validity: Italy – Emissions

Sector	MtCO2 Emissions			
	2019	2020	Diff.	Pct. Diff.
Domestic Aviation	1.89	1.00	0.89	47.02
Ground Transport	91.13	81.63	9.50	10.42
Industry	54.39	47.75	6.64	12.21
Residential	74.95	73.92	1.04	1.38
	Counterfactual	Realized	Diff.	Pct. Diff.
Power (lower bound)	76.18	74.31	1.87	2.45
Power (upper bound)	103.62	101.08	2.54	2.45
Total (lower bound)	298.54	278.61	19.93	6.68
Total (upper bound)	325.98	305.38	20.60	6.32

Lower bound assumes carbon intensity of 272 gCO2/kWh (avg. of sector)

Upper bound assumes carbon intensity of 370 gCO2/kWh (CCGTs)

External Validity: Italy – GDP



Short-term GDP loss = 145.48 Billion Euros

Implicit cost of carbon = 7,062 Euro/Ton for Italy.

Simulations Using Predictions from FE

	Counterfactual Demand (FE Model)		Realized Demand		Difference	
CO_2 (M Ton)	Competitive	Strategic	Competitive	Strategic	Competitive	Strategic
Coal	3.36	3.87	3.08	3.52	0.28	0.35
Gas	23.55	23.36	18.00	17.85	5.55	5.51
Cogen + Others	11.21	11.56	10.87	11.49	0.34	0.07
Total	38.11	38.79	31.94	32.86	6.16	5.93

Abatement estimates are substantially higher with these simulations: assuming competitive behavior, abatement was 6.16 Million Tons (almost 50% higher than those from ML).